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TECHNICAL MEMORANDUM NO. 3

EXTINCTION COEFFICIENT MEASUREMENTS ON CLEAR ATMOSPHERES AND THIN CIRRUS CLOUDS

SPACE SCIENCES LABORATORY
GENERAL ELECTRIC
MISSILE AND SPACE DIVISION

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EXTINCTION COEFFICIENT MEASUREMENTS ON CLEAR ATMOSPHERES AND THIN CIRRUS CLOUDS

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GENERAL ELECTRIC COMPANY
Missile and Space Division
Space Sciences Laboratory

ABSTRACT

An experimental investigation was carried out to determine possible differences in visible light extinction properties of continental and maritime air. Urban, desert and oceanic atmospheres were probed by means of a stable photodiode radiometer using direct sunlight as the source. No major differences were found for the three locations. Experimental coefficients generally lie slightly below model data, though significantly higher than would be expected from purely molecular scattering. Day-to-day variations of up to 30% were found. Results of similar extinction measurements on thin cirrus clouds show a slight increase in scattering coefficient in going from 4000 to 7000 Å wavelength.

1.0 INTRODUCTION

Visible and near ultraviolet radiation passing through the telluric atmosphere is attenuated primarily by molecular and large particle scattering. In the absence of clouds, the dominant scatterers over continental regions are diatomic molecules and sub-micron size solid particles[1] suspended in the form of an aerosol. Elterman[2] published a detailed model of clear air extinction coefficient variation with altitude for continental regions. However, maritime atmospheres can be considerably different since the nature and concentration of the aerosols are undoubtedly not the same as those found over continental land masses.

In practical considerations involved in light measurements through the atmosphere one must also consider the effect of clouds, particularly insofar as they may distort the spectral distribution of the source radiation. Heavy cumulus or stratus can readily be detected by their obvious attenuation. However, the more prevalent cirrus, and particularly cirrostratus, are frequently quite thin and specularly transmitting. Such clouds are difficult to detect visually at night and frequently even in daytime.

In this paper we describe results of recent measurements of clear air extinction coefficients made at three different locations of wide climatic variation. Of greatest interest are possible differences that may exist between continental and oceanic atmospheres. Table 1 gives the coordinates of the three measurement sites. Cirrus data were acquired at the mid-Pacific site where clouds are more prevalent and where their optical effects are, therefore, of greater concern.

Table 1. Coordinates of Measurement Sites

Location	Latitude	Longitude	Altitude (ft.)	Environment Type
Valley Forge, Pa.	40^{o} 04.9' N	75^{o} 23.3' W	200	urban
White Sands, N.M.	32^{o} 56.9' N	106^{o} 04.5' W	4020	desert
Kwajalein, M.I.	8^{o} 43.4' N	167^{o} 43.7' E	20	maritime

2.0 EXPERIMENTAL

All measurements were carried out by means of a highly stable, filtered radiometer using the sun as a background source. A biplanar vacuum photodiode radiometer (EG&G Model 58) with an S-20 response detector (ITT FW 114A) was used because of its excellent long term radiometric stability and high degree of linearity over a wide dynamic range (about 10^5). Its relatively low sensitivity was of no consequence in these solar measurements. The instrument had a minimum noise equivalent irradiance of about 3×10^{-10} w/cm^2 at 5500 Å. The collimating tube was 50 cm long, and 3.1 and 3.6 cm in diameter at the two ends. This configuration was set up to yield a flat field response over a 1/2 degree viewing cone, with the response dropping to zero at about 4 degrees off axis. In this manner, the ratio of direct sunlight to surrounding skylight sensed by the detector was maximized.

A series of seven interference filters was used to yield nearly monochromatic measurements at equally spaced wavelengths in the region 4000 to 7000 Å. Figure 1

shows the actual bandpass functions of the filters along with the normalized spectral response of the radiometer.

In practice, the sun was tracked manually for several hours before and/or after noon with the instrument head mounted on a tripod. Readings were recorded with each of the seven filters at 15 to 30 minute intervals, provided that no obvious cloud obscuration was present. Before each reading, the instrument was adjusted in elevation and azimuth to give peak signal. A one percent variation in light intensity could be readily detected. This high level of sensitivity also enabled the detection of light clouds, which invariably resulted in rapid signal variations as a result of their motions. Thus, visual observation of clear sky in the sun direction followed by a steady radiometer signal was a good indication of the absence of all but very thin clouds.

Sun coordinates corresponding to each reading were computed from the recorded timing and data in the Nautical Almanac.[3] Using nominal air mass calculations for a spherical atmosphere, including the effect of refraction,[4] the radiometer signals for each wavelength were plotted as a function of air mass in the usual semi-log format to yield straight line approximations in accordance with Beer's law.[5]

With the instrument kept in the same configuration, zero air mass photocurrent extrapolations for two sets of data recorded 4-1/2 months apart show long term absolute radiometric stability within $\pm$ 5% (Table 2). With the zero air mass solar intensity points thus established during clear air days, it was subsequently possible to interpret any other individual reading directly in terms of atmospheric transmittance to a similar accuracy.

Table 2. Long Term Stability of Radiometer used in Atmospheric Measurements

Wavelength (Å)	Zero-Air Intercept (μ amp) 9/20/67	2/6/68	% Deviation from Mean
4000	1.06	1.06	0
4500	3.04	3.08	+0.6
5000	4.30	4.60	+3.5
5500	3.10	3.04	-1.0
6000	1.72	1.64	-2.5
6500	.705	.672	-2.5
7000	.345	.310	-5.6

3.0 MEASUREMENT RESULTS

Clear air measurements were made at Valley Forge, Pa. on 6 November 1967, and 6 & 19 February 1968. Scattered cumulus clouds appeared on 6 November. However, these did not interfere seriously with the measurements except during two brief periods (Figure 2). As can be seen from Figure 2, good straight line fits are obtained for air masses two to seven. The almost total absence of clouds on February 6 and 19 resulted in even better logarithmic fits as can be seen in Figure 3 where we plot radiometer current on a log scale vs. air mass for the morning and afternoon of February 6. Similar data quality resulted from the White Sands measurements for the afternoon of November 20 (Figure 4). No clouds were observed on that day so that high quality data could be obtained down to 10 air masses. The ordinates of Figures 2 and 4 were normalized to unity so that they represent transmittance from ground to infinity.

Sky conditions at the mid-Pacific site on Kwajalein were considerably more overcast during the measurement period January 5-18. Rapidly moving scattered

cumulus clouds were present on most days and were continuously changing as a result of the high trade winds. In addition to these, very light extended cirrus could be observed at much higher altitudes on most days. Because of their stratified nature and low optical thickness, these were frequently difficult to detect visually since the sky appeared generally blue through these clouds and the solar disc was well defined. Viewing the sun through a density 3 filter revealed no halo during times of measurement, although such a halo is normally associated with cirrus clouds.[6]

From all indications, the Kwajalein sky on January 5 appears to have been free of cirrus with only slight cumulus present. The data for this day, shown in Figure 5, substantiates this conclusion since a fair degree of homogeneity of atmospheric scatterers is indicated down to six air masses. Furthermore, extrapolations to zero air mass are in excellent agreement with measurement results of 6 February at Valley Forge (also see Table 2). Results for January 8, 10, 12, 15, 17 and 18 are subject to progressively more interference by transparent cirrus clouds, with the afternoons of the 12th and 17th having the heaviest, though still transparent, overcast. Relative intensity vs. air mass plots for these days are shown in the appendix. It is interesting to note that straight line approximations with the correct zero-air intercepts can be made for even the worst cirrus days. Since each set of data refers to a widely extended portion of the sky, the linear results indicate the presence of relatively constant thickness cirrostratus covering large areas.* Data for January 12 and 17, for example, indicate two distinct slopes

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*A scattering medium distributed in the form of a uniform slab will result in extinction coefficient proportional to sec θ, where θ is the angle of incidence. For θ (zenith angle) approaching 90^o, the extinction due to stratus will approximately follow the air mass for a curved atmosphere.

for the AM and PM observations. Although both sets show reasonable straight line behavior down to zenith distances as high as 80^o, the afternoon skies on both days yield a distinctly higher extinction or optical thickness than the corresponding morning sky. As will be shown later, the transmission at the zenith through all these clouds was greater than 70% and, hence, such clouds are not readily detectable visually, particularly in view of their uniform and extended nature. Night-time detection of such cloud cover is even more difficult.

4.0 ANALYSIS

The atmospheric extinction coefficient, τ, is usually normalized to unit air mass, w , such that Beer's law is expressed as

$$I = I_0 e^{-\tau w} \tag{1}$$

where I denotes the intensity at the ground, I_0 the corresponding value for zero air mass, and w is the ratio of integrated air density along the path of observation normalized to the zenith value. For zenith angles, θ , up to 80^o (w = 5.7) air mass may be approximated by sec θ to an accuracy of 3%. Closer to the horizon, data corrected[4] for earth's curvature and refraction were used.

Extinction coefficients measured at White Sands (4160 ft. above sea level) are compared with the continental model[2] in Figure 6. In general, τ could be determined from the data to a precision of $\pm$ .008. Apparently, the effects of aerosol scattering at White Sands were not nearly as large as indicated by the model. Except for a slight hump at 6000 Å, probably due to water vapor absorption, the measured extinction coefficient is a nearly constant .03 above that predicted on the basis

of molecular scattering, while it is on the average .06 lower than that given by the aerosol scattering model. At 7000 Å, the measured coefficient is nearly twice the Rayleigh value whereas at 4000 Å it is only 10% higher. Thus, a significant contribution from aerosols is evident, though not nearly as large as given by the model data.

Results of the Valley Forge measurements are compared with model data in Figure 7. Again, the model shows a slight tendency to overestimate the effect of aerosols, though the mean values for the three days are considerably closer to the aerosol model than was the case at White Sands. At 7000 Å, the mean measured value is 3.5 times the Rayleigh value while at 4000 Å, it is 50% higher. The day-to-day variation, on the other hand, indicates a nearly constant 20-30% systematic change over the entire visible spectrum. Since the spectral distribution was found unchanged, these daily variations are attributed directly to similar percent changes in total concentration of atmospheric scatterers.

Unlike the spectrally flat day-to-day variations in the Valley Forge data, the extinction coefficients for Kwajalein shown in Figure 8 display an entirely different nature in their variation. Excluding the results for the afternoon of the 12th, the spread in τ goes from 10% in the blue to 70% in the red. The systematic increase in extinction coefficient from January 5 to January 17 is attributed to a gradual increase in the general level of cirrus overcast which was also observed, though with some difficulty, visually. It can be seen that the scattering contribution from cirrus on the afternoon of the 12th was particularly strong. This again was confirmed visually.

All indications are that the data shown for January 5 are representative of a clear atmosphere for the Kwajalein region. The relationship of these data with respect to the model curves is quite similar to that found for the continental measurements. It is somewhat surprising that this should be the case since a maritime atmosphere would be expected to contain a different type and concentration of aerosols than would be found over a land mass. In all cases discussed in this paper, the contribution of scattering by aerosols in the red is on the same order of magnitude as that due to molecular scatterers. Thus, measurements in the red portion of the spectrum give a sensitive indication of the concentration of aerosols, while the ratio of red-to-blue describes their type, e.g., size, size distribution, etc. In terms of these parameters, no major differences could be observed between the continental and maritime atmospheres.

Having assumed that January 5 was a representative clear day at Kwajalein, the extinction coefficients for that day were used as a baseline to deduce the transmission spectra of thin cirrus clouds for the remainder of the observation period. These are shown in Figure 9 where we show the wavelength dependence of the extinction coefficients attributed to cirrus clouds, which consist of small ice crystals.[6] Also shown as the right-hand ordinate is a scale of specular transmittance at normal incidence. Earlier description of the data has indicated that Equation 1 is a good approximation for the observed cirrostratus, as well as for the clear atmosphere.

As may be expected, the data of Figure 9 reveal a variation in the cloud thickness from day to day. However, in all cases there is a gradual increase in τ from blue to red by an amount varying from .05 to .1 depending on the cloud thickness. Thus, spectroscopic measurements through such clouds at the zenith will

result in maximum spectral distortions of 5 to 10% in the indicated spectral range. At 30° elevation angle, these spectral distortions would double. Absolute intensity measurements through this type of cirrus at normal incidence would be subject to errors of less than 25% even for the worst case observed.

5.0 SUMMARY

Measurements of atmospheric extinction for urban, desert, and maritime environments show no major differences in clear air scattering of visible radiation. Experimental extinction at all three locations lie in a band bracketed by pure Rayleigh scattering and combined Rayleigh and aerosol scattering as described by a recently published model by Elterman.[2] Day-to-day variations in τ of as much as 30% were found for the industrial atmosphere. This variation was nearly independent of wavelength and is, therefore, attributed to changes in concentration of scatterers rather than type. The clear air measurements data at the desert site indicate a somewhat more transparent atmosphere than was found at the other locations. However, no significant differences in the scattering spectra were found between continental and maritime air.

Based on the clear air transmission data from the Pacific site, extinction coefficients for optically thin cirrus clouds were inferred. In going from 4000 to 7000 Å, these clouds show a slight increase in τ, from .05 to .1 depending on the cloud thickness. Thus, a 5 to 10% systematic spectral distortion may be expected in looking at a source through such clouds at normal incidence.

ACKNOWLEDGEMENT

Much of the credit for the success of this study is due to Mr. James Hurley, a member of the Project GLOW staff at the Kwajalein Test Site. His very patient and meticulous daily data gathering activity during a period of several weeks required continuous visual monitoring of the sky and careful control of the radiometer operation.

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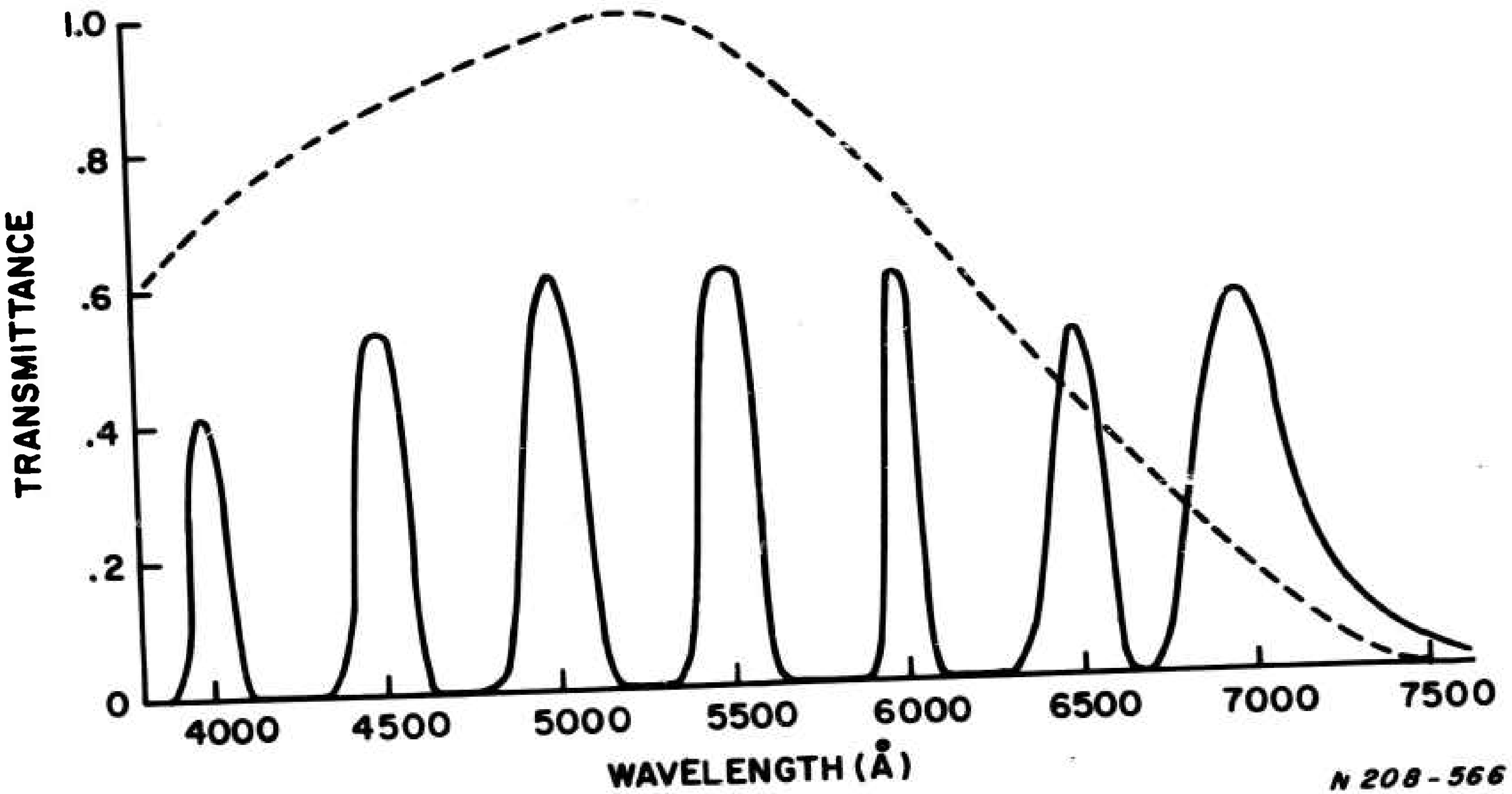


Figure 1. Spectral transmission curves for bandpass filters used with radiometer whose normalized spectral response is shown by dashed curve.

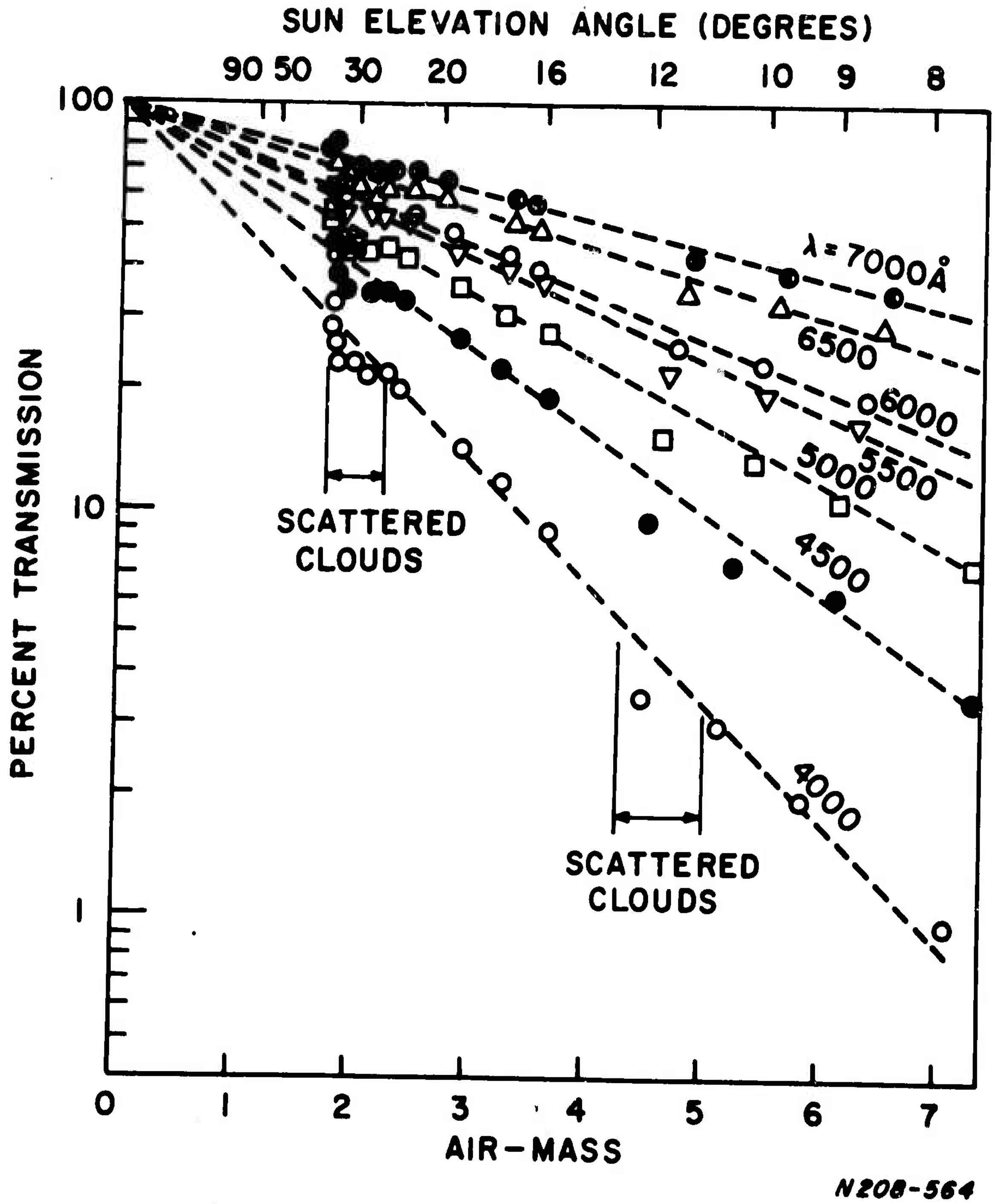


Figure 2. Atmospheric transmission vs. air mass at Valley Forge, Pa. on 6 November 1967 inferred by normalization at zero air mass. Straight lines were fitted to original radiometer current readings by disregarding data in the vicinity of clouds.

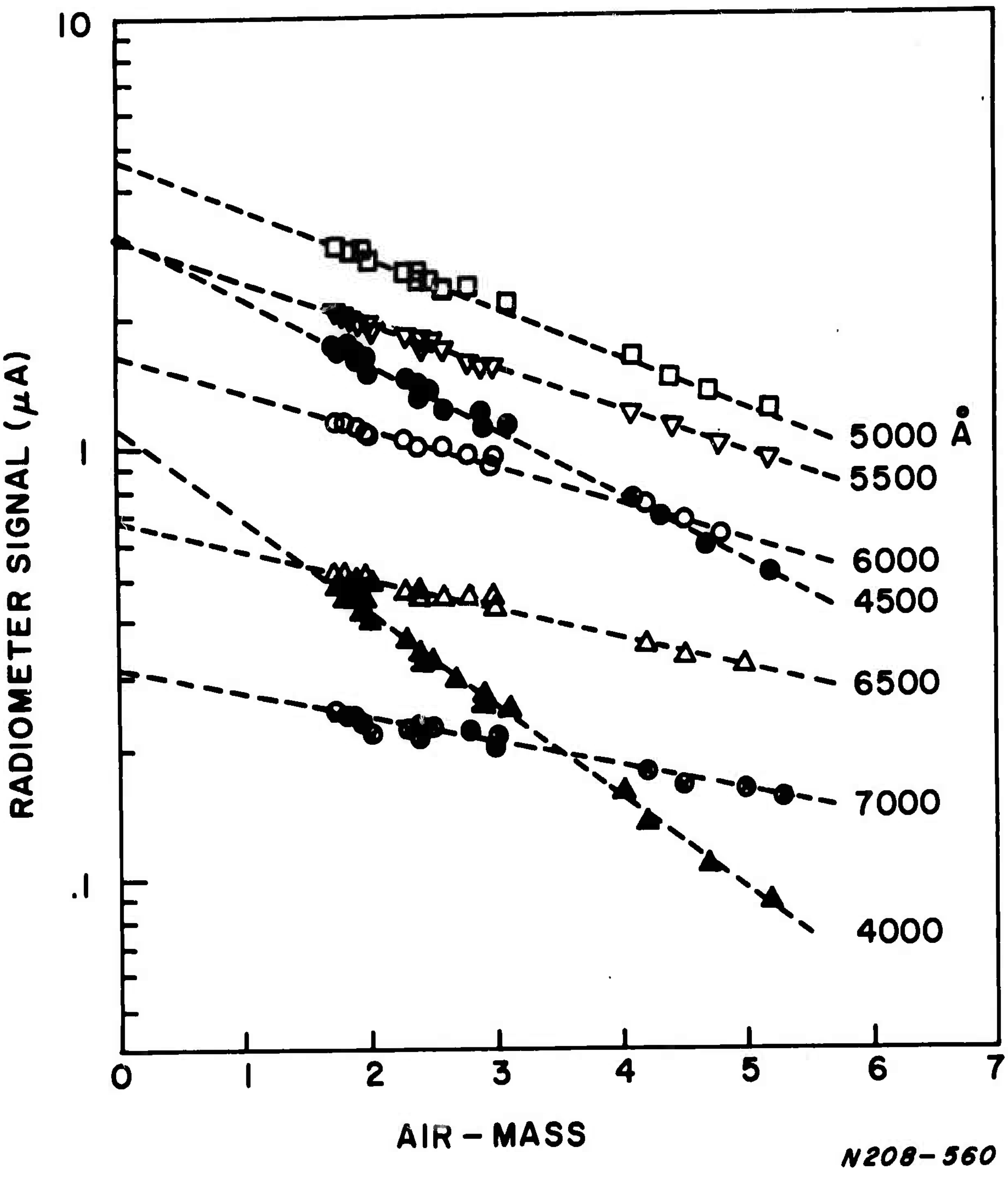


Figure 3. Radiometer signals (photo current) for direct sunlight recorded at Valley Forge on 6 February 1968. Below 3 air masses, data were taken in AM and PM skies.

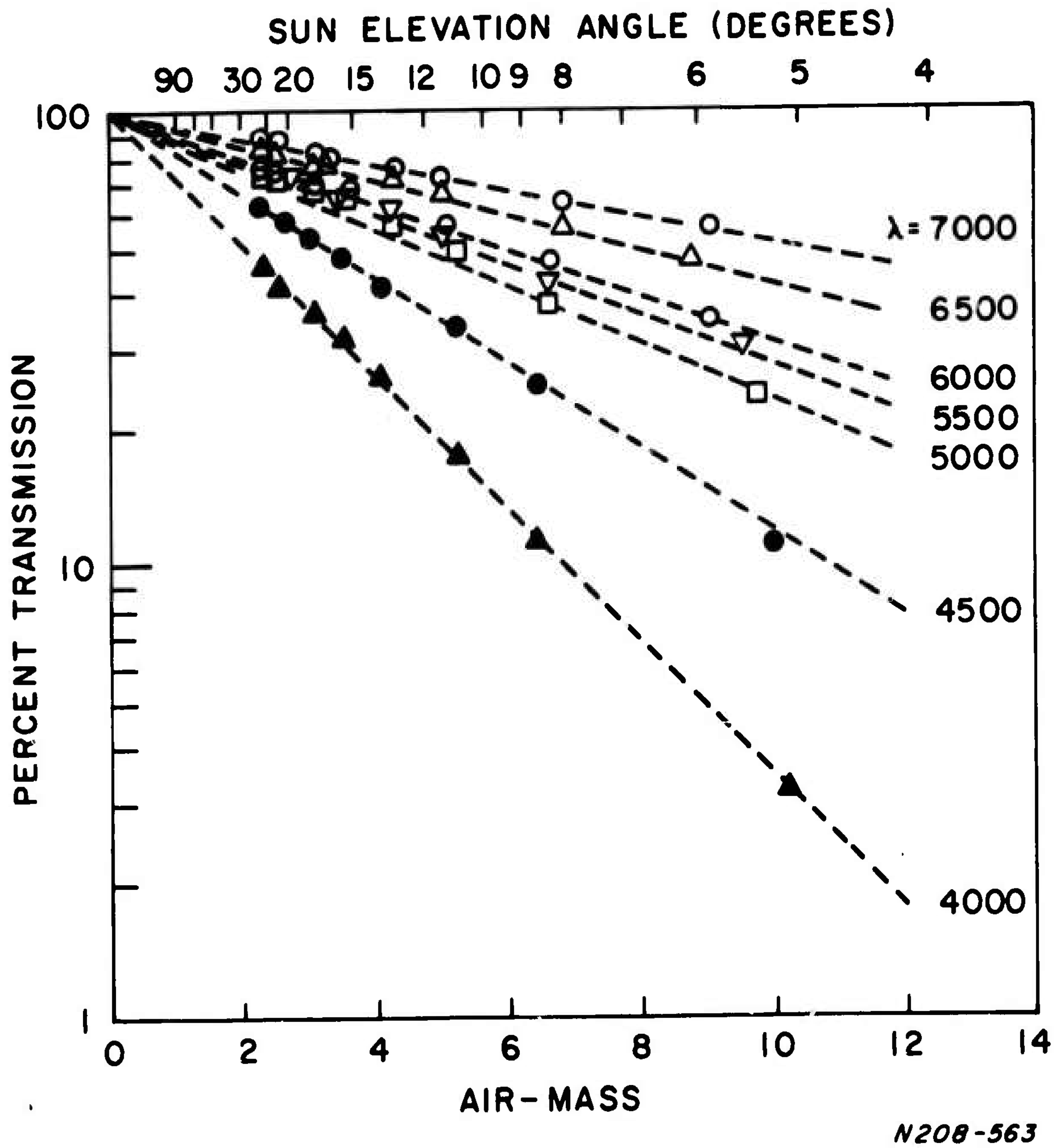


Figure 4. Atmospheric transmission vs. air mass as measured at White Sands, 20 November 1967.

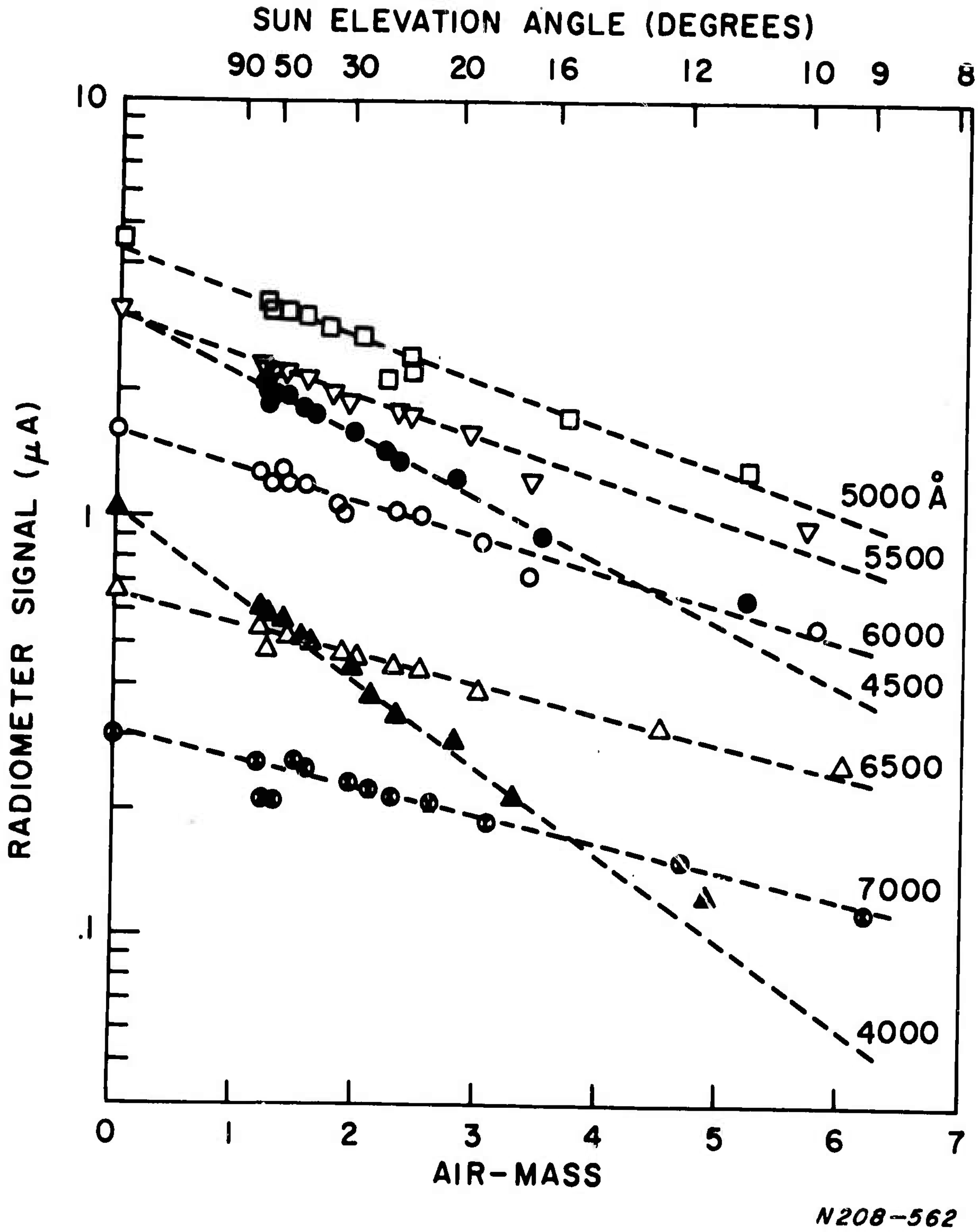


Figure 5. Radiometer signals (photo current) for direct sunlight recorded on Kwajalein Island, 5 January 1968. Zero air-mass intercepts are from similar measurements with same instrument at Valley Forge on 6 February 1968. Dashed curves are straight line fits at i. licated wavelengths.

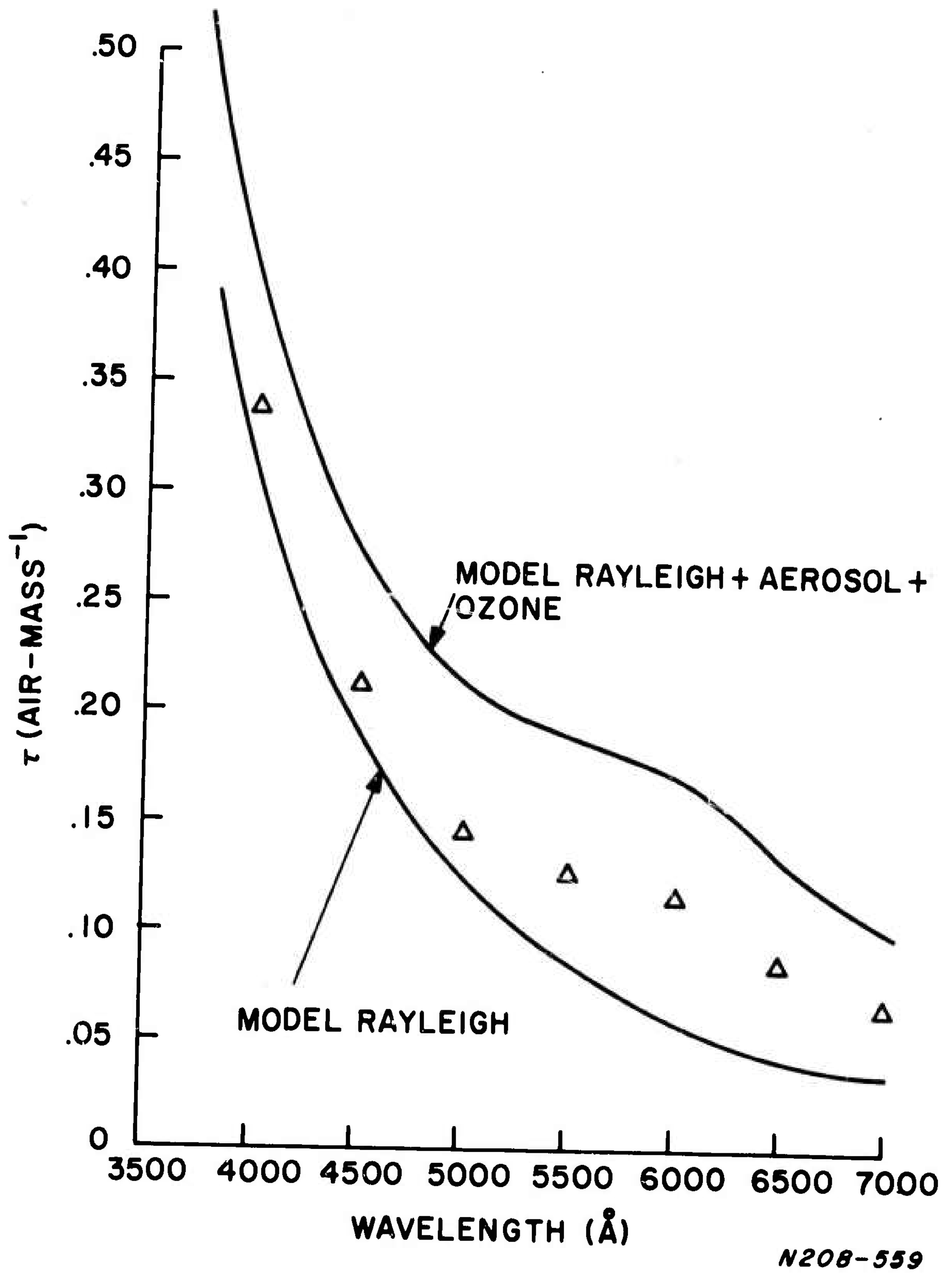


Figure 6. Atmospheric extinction coefficient τ measured at White Sands Δ compared with published model.

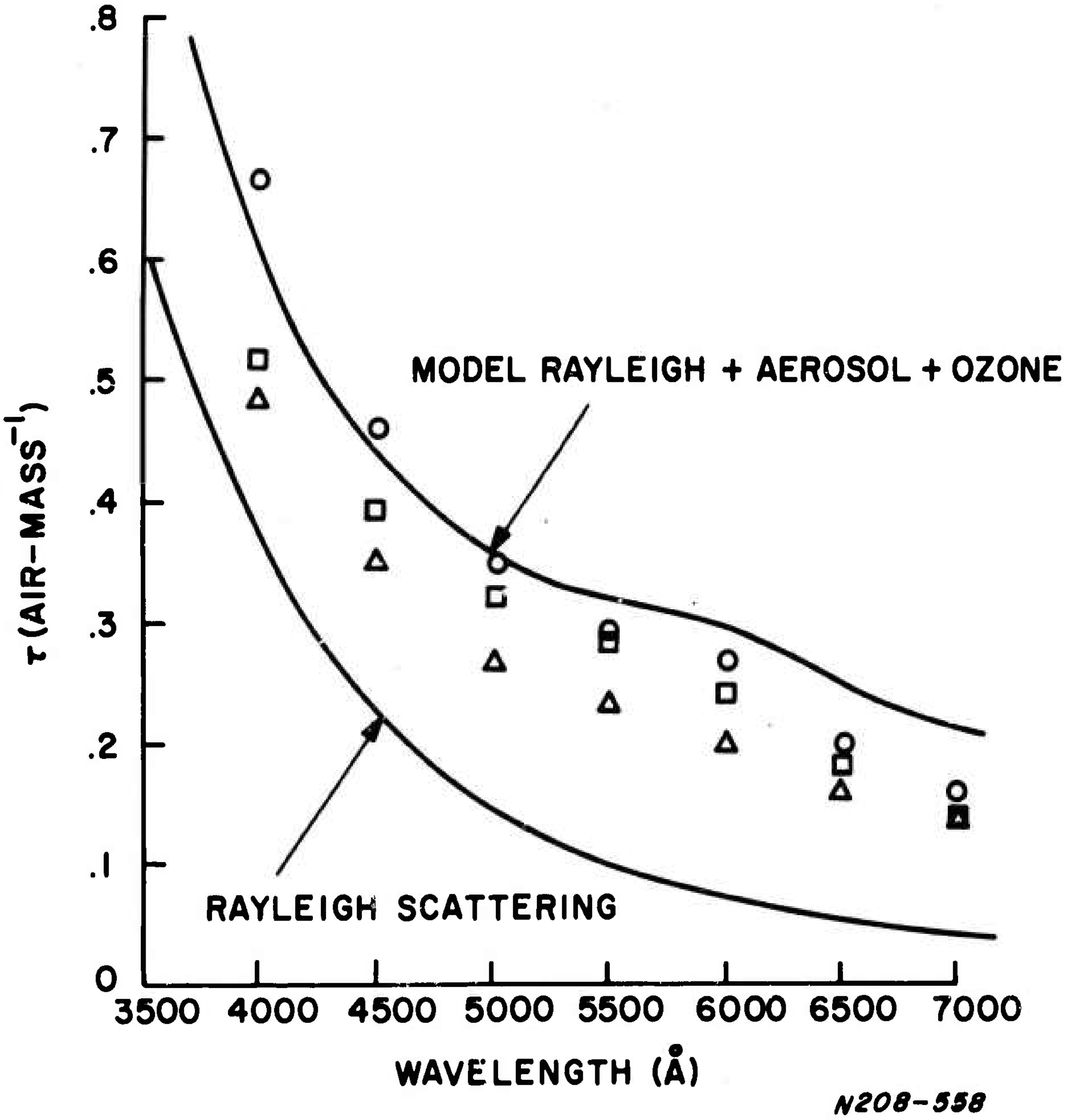


Figure 7. Atmospheric extinction coefficient measured at Valley Forge compared with published model. Measurements were made on 6 November 1967 ○ , 6 February 1968 △ and 19 February 1968 □ .

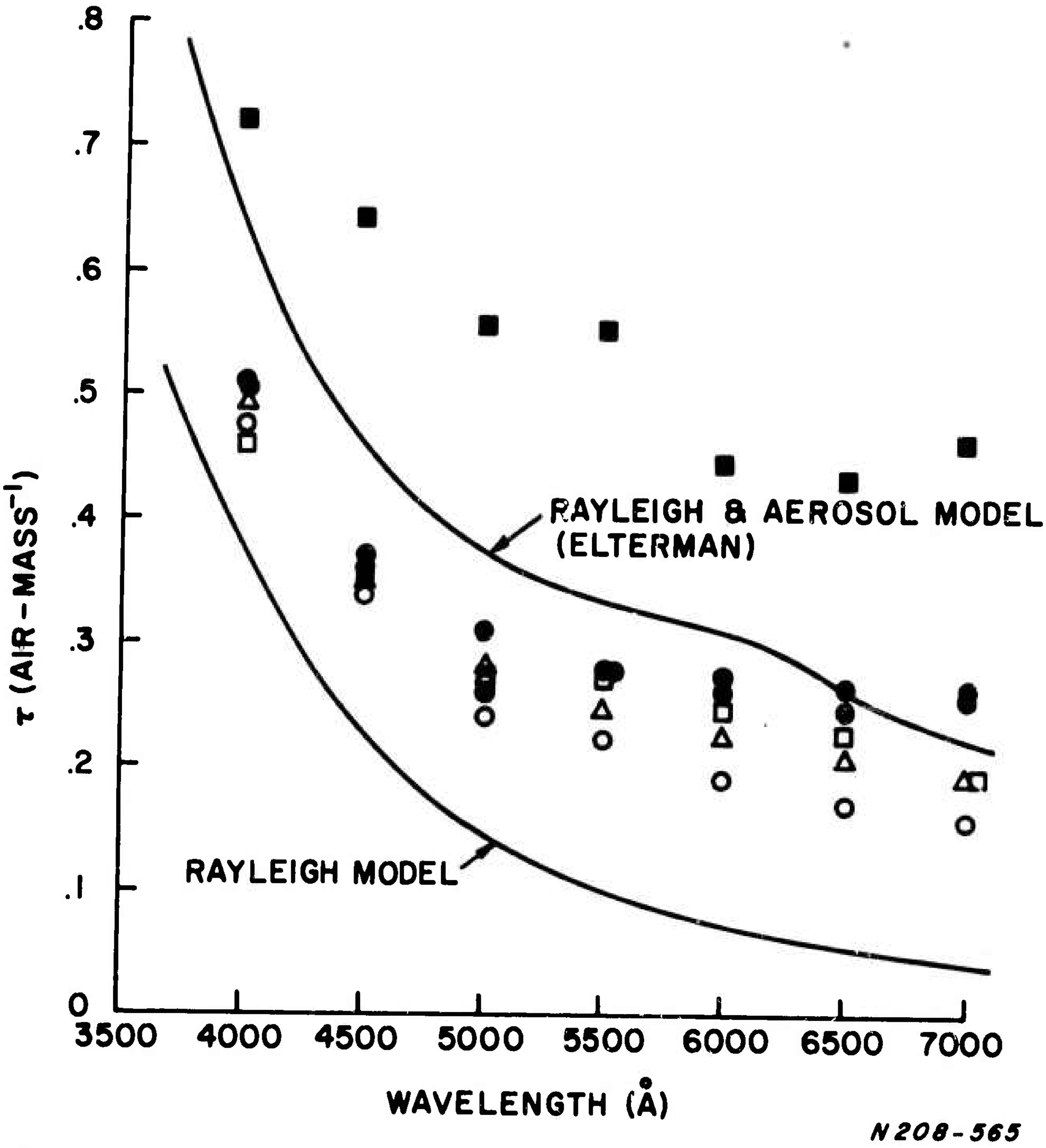


Figure 8. Extinction coefficients of Kwajalein clear atmosphere (1/5/67) and in the presence of specularly transmitting thin cirrus clouds compared with scattering models. Measurements were made on 5 Jan 68 ○, 8 Jan △, 12 Jan AM □, 12 Jan PM ■, 15 Jan ⊗, and 17 Jan ●.

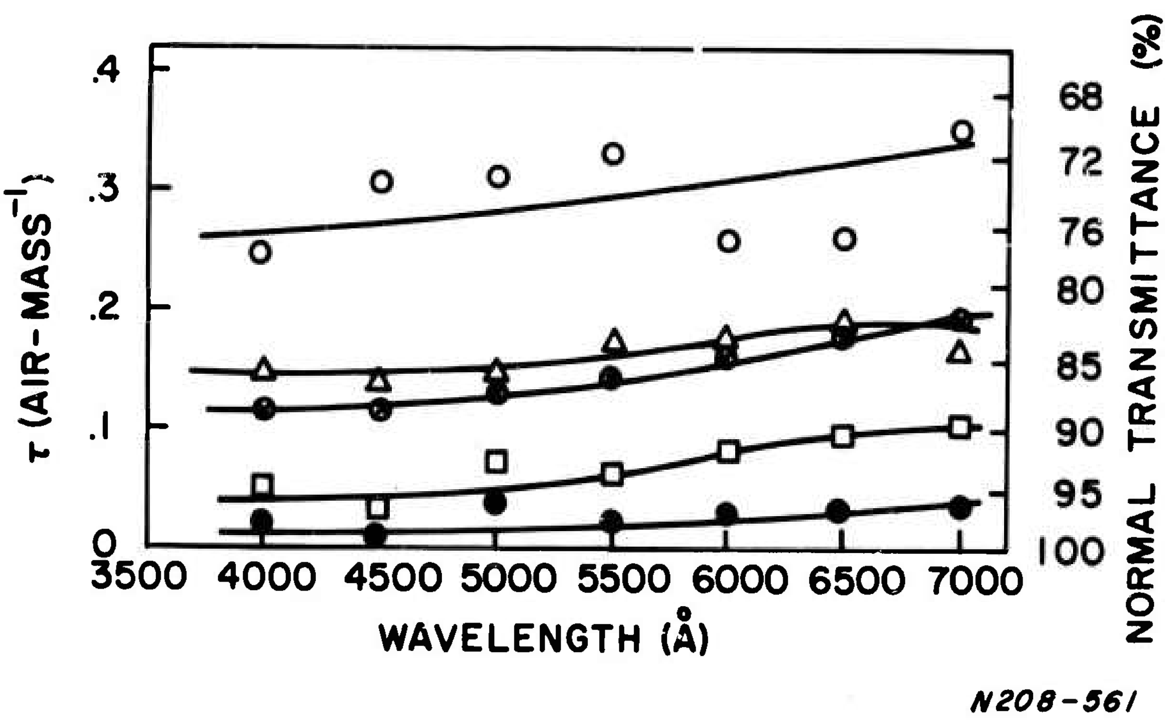
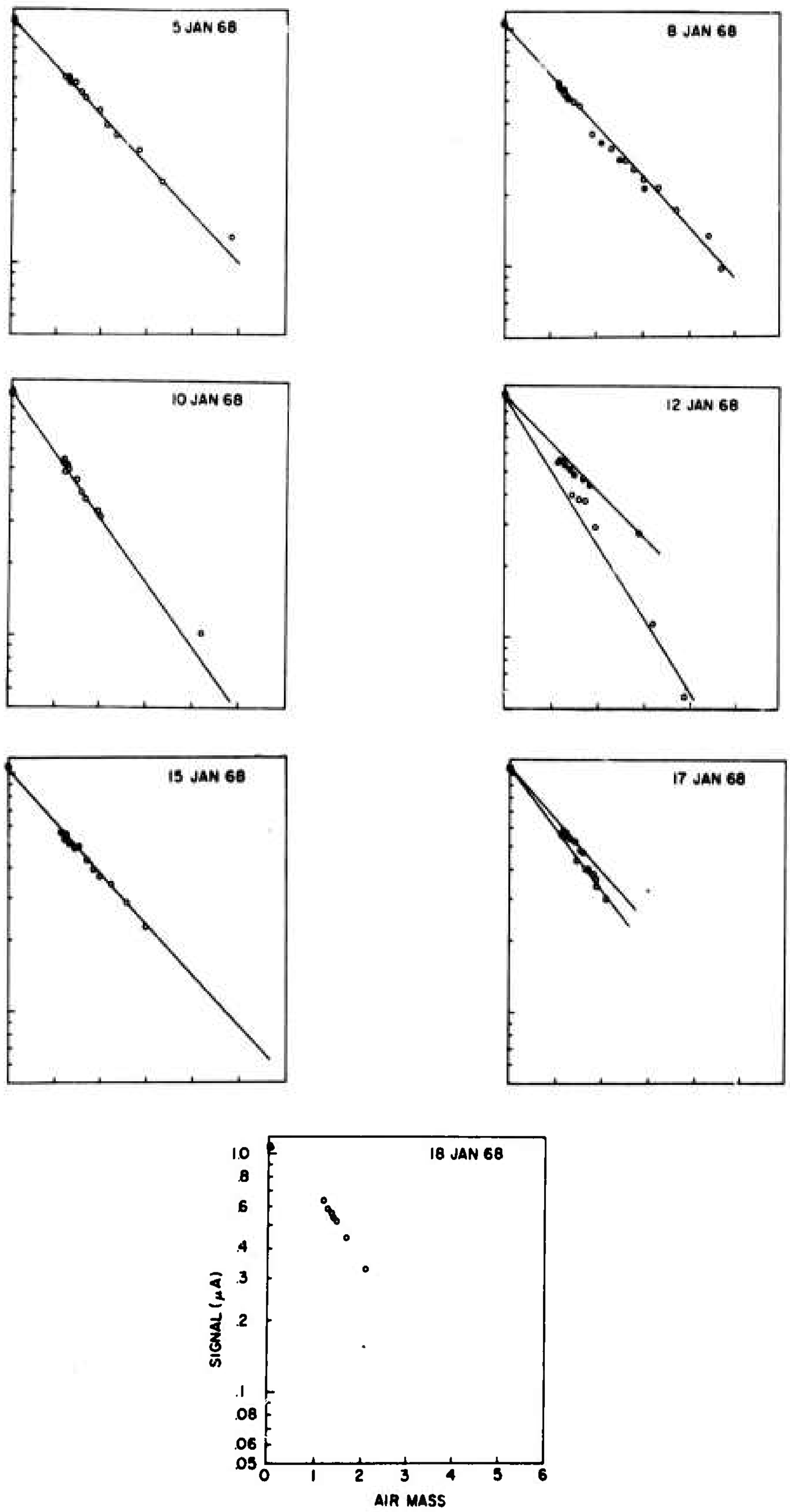


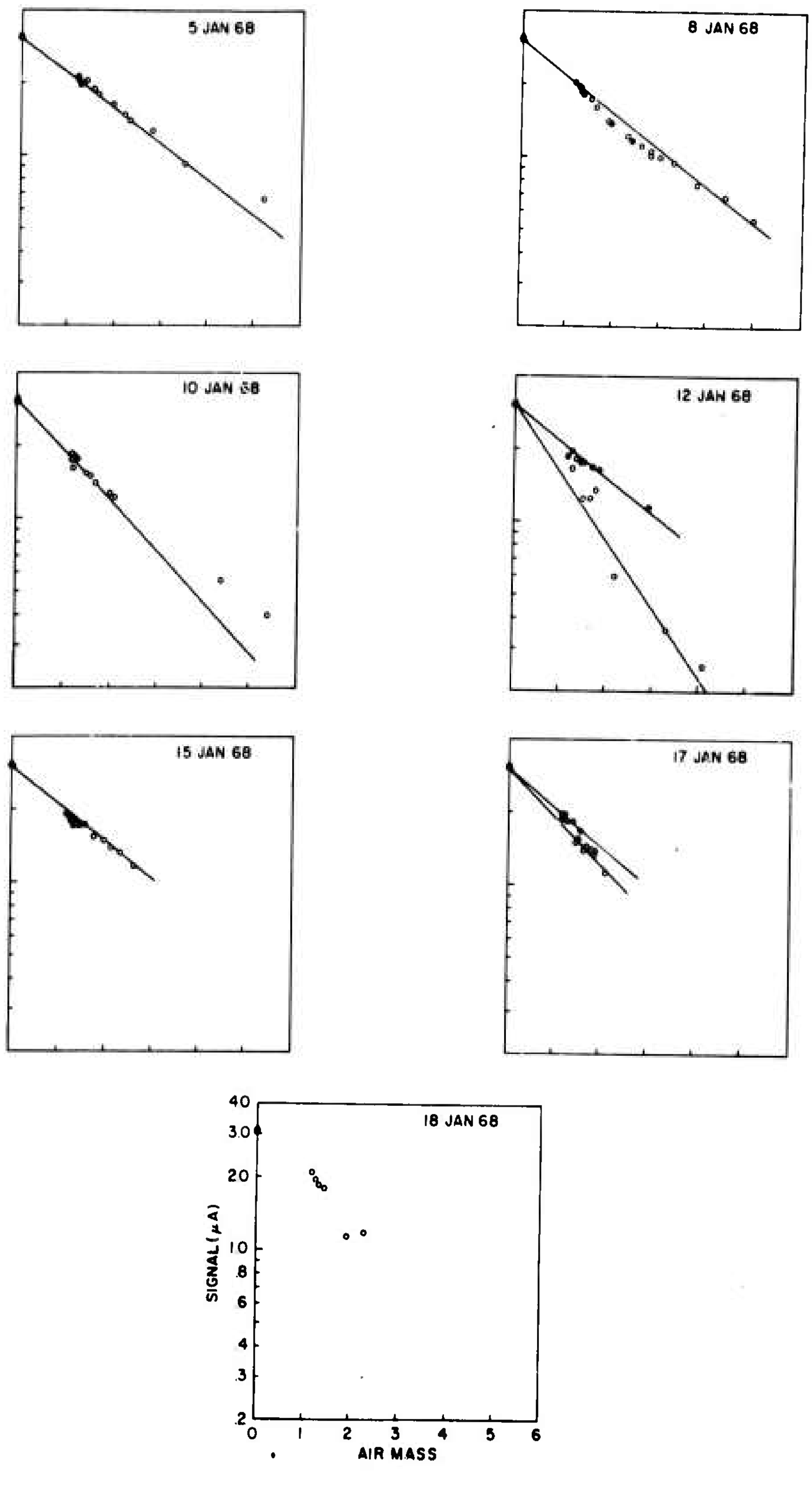
Figure 9. Extinction coefficient for optically thin cirrus clouds observed at Kwajalein Island. Data refer to 8 January PM ●, 10 January PM △, 12 January PM ○, 17 January AM □, and 17 January PM ⊗.

APPENDIX

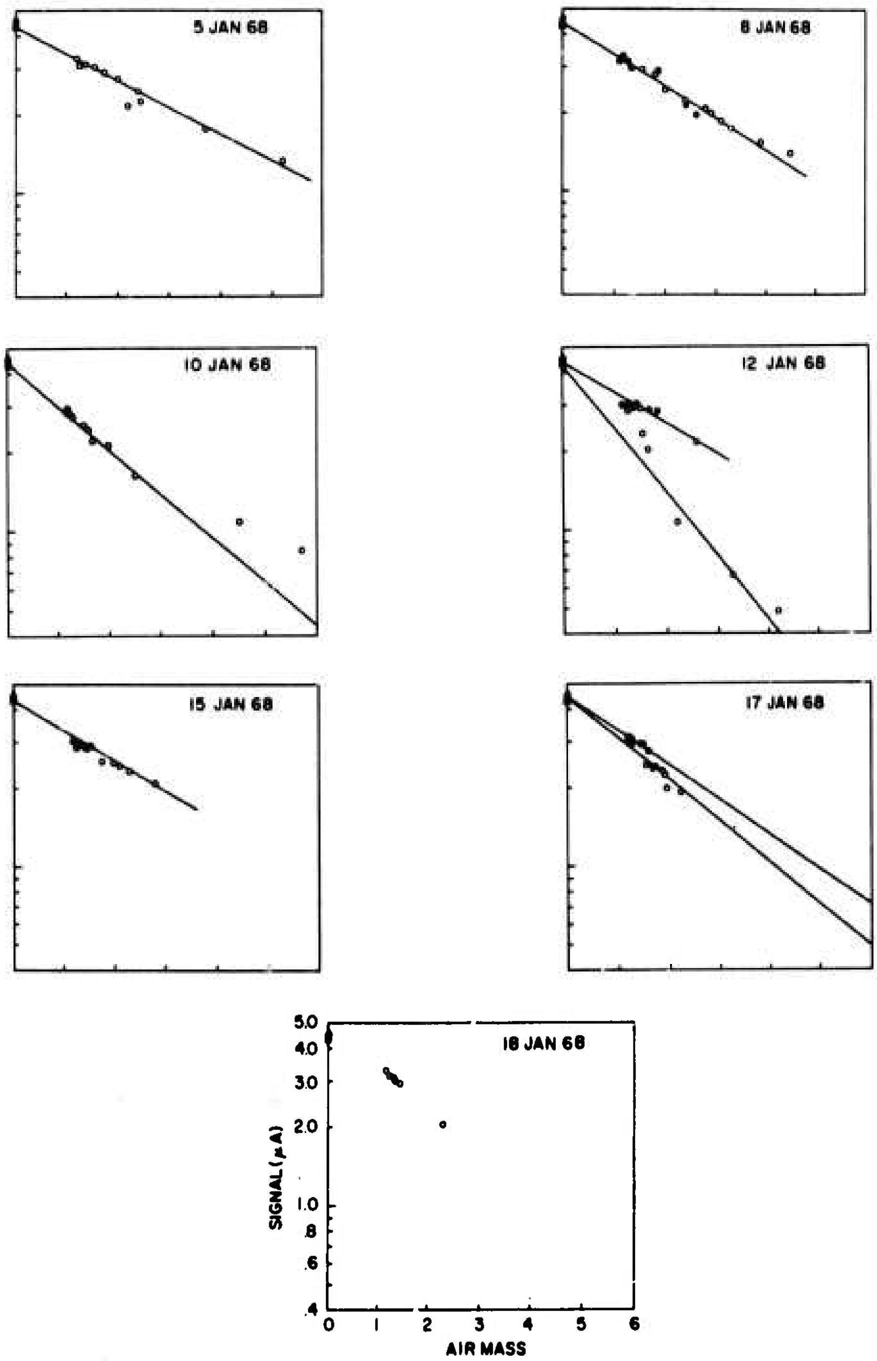
Radiometer signals for direct sunlight are plotted as a function of air-mass for the Kwajalein site. Open circles are for PM, solid circles for AM data. Zero intercepts are based on measurements with the identical instrument configuration on 9/20/67 □ and 2/6/67 △ . Straight lines were used in deriving extinction coefficients. All data for a given wavelength are plotted to same scales.



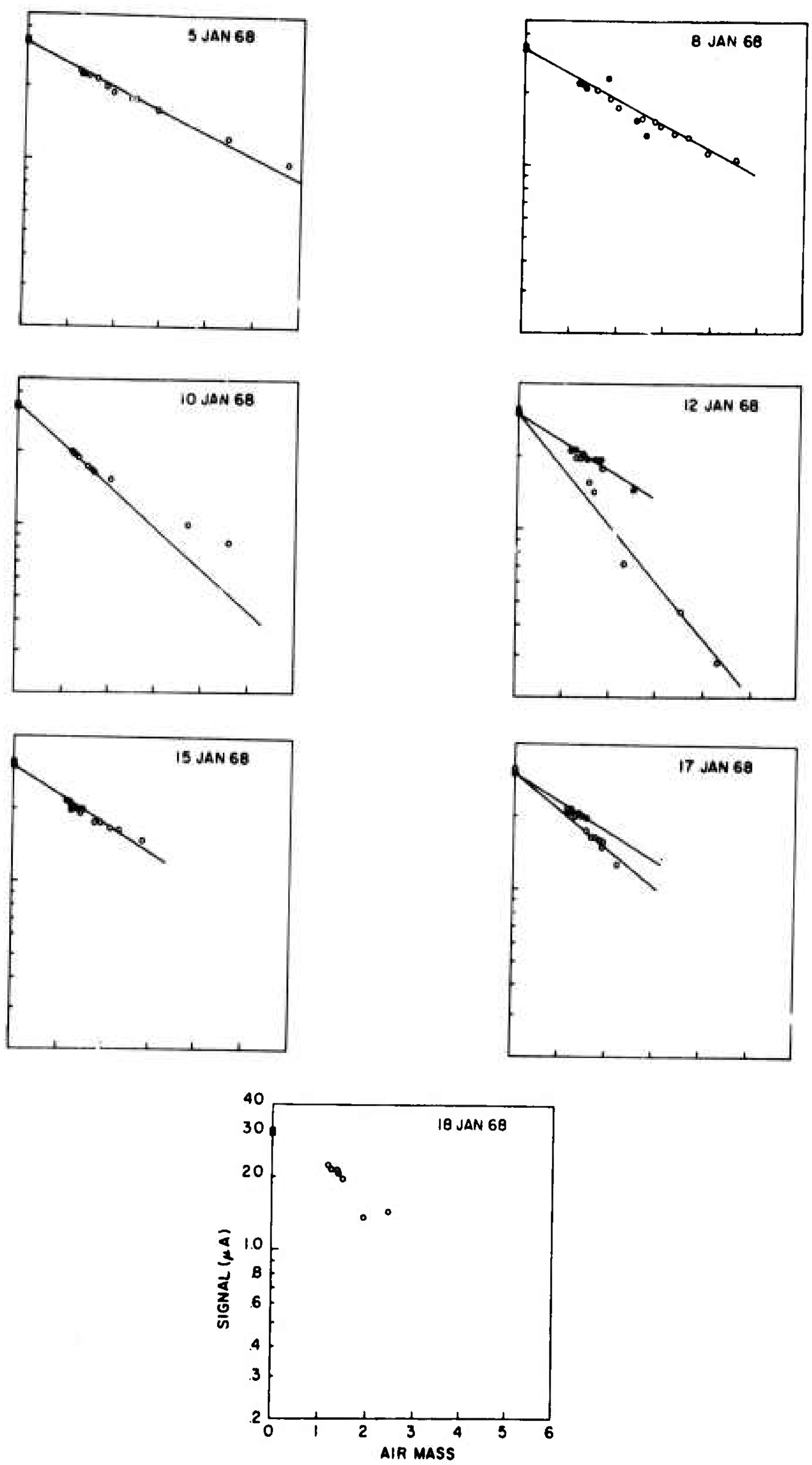
(a) $\lambda = 4000$ Å



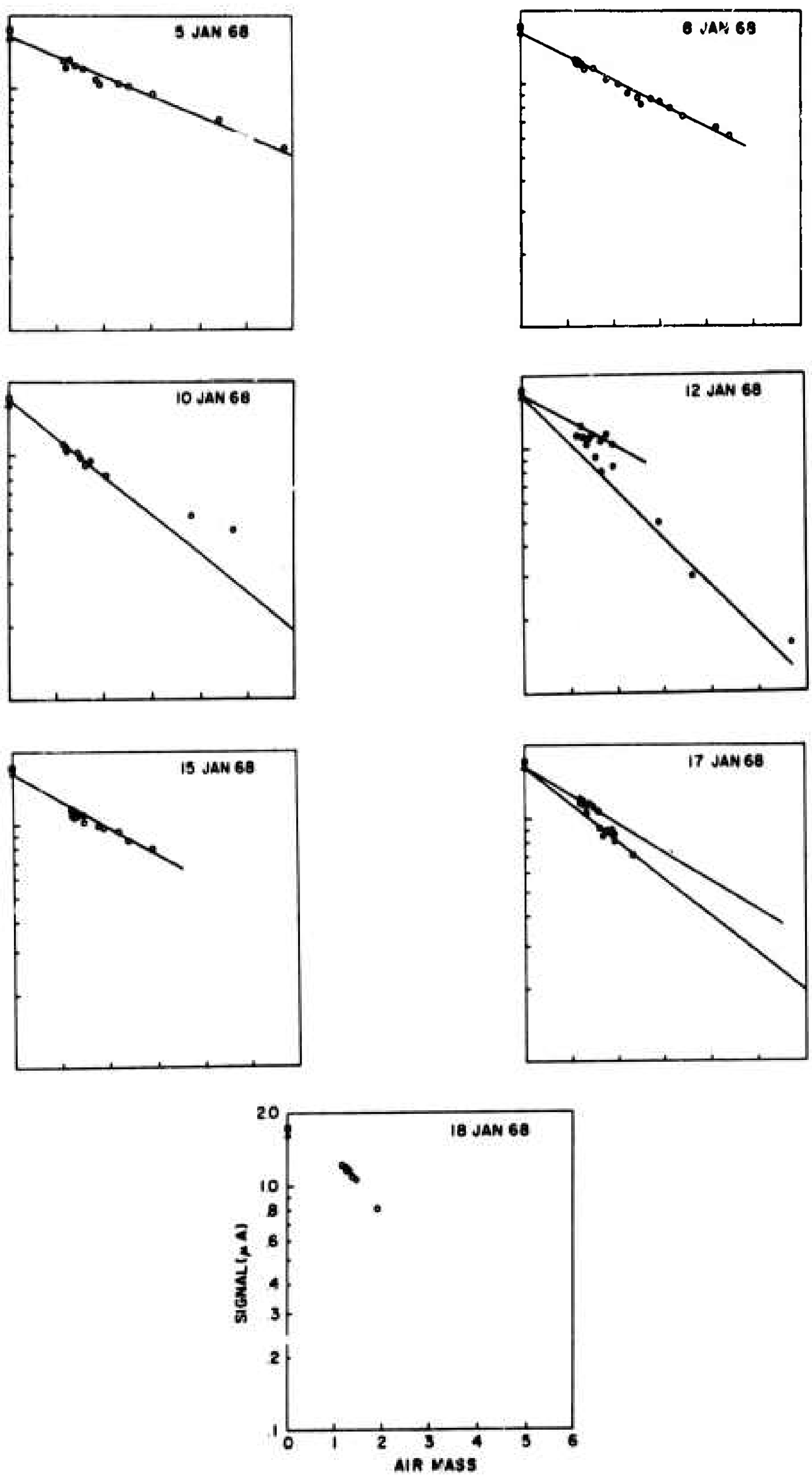
(b) $\lambda = 4500$ Å



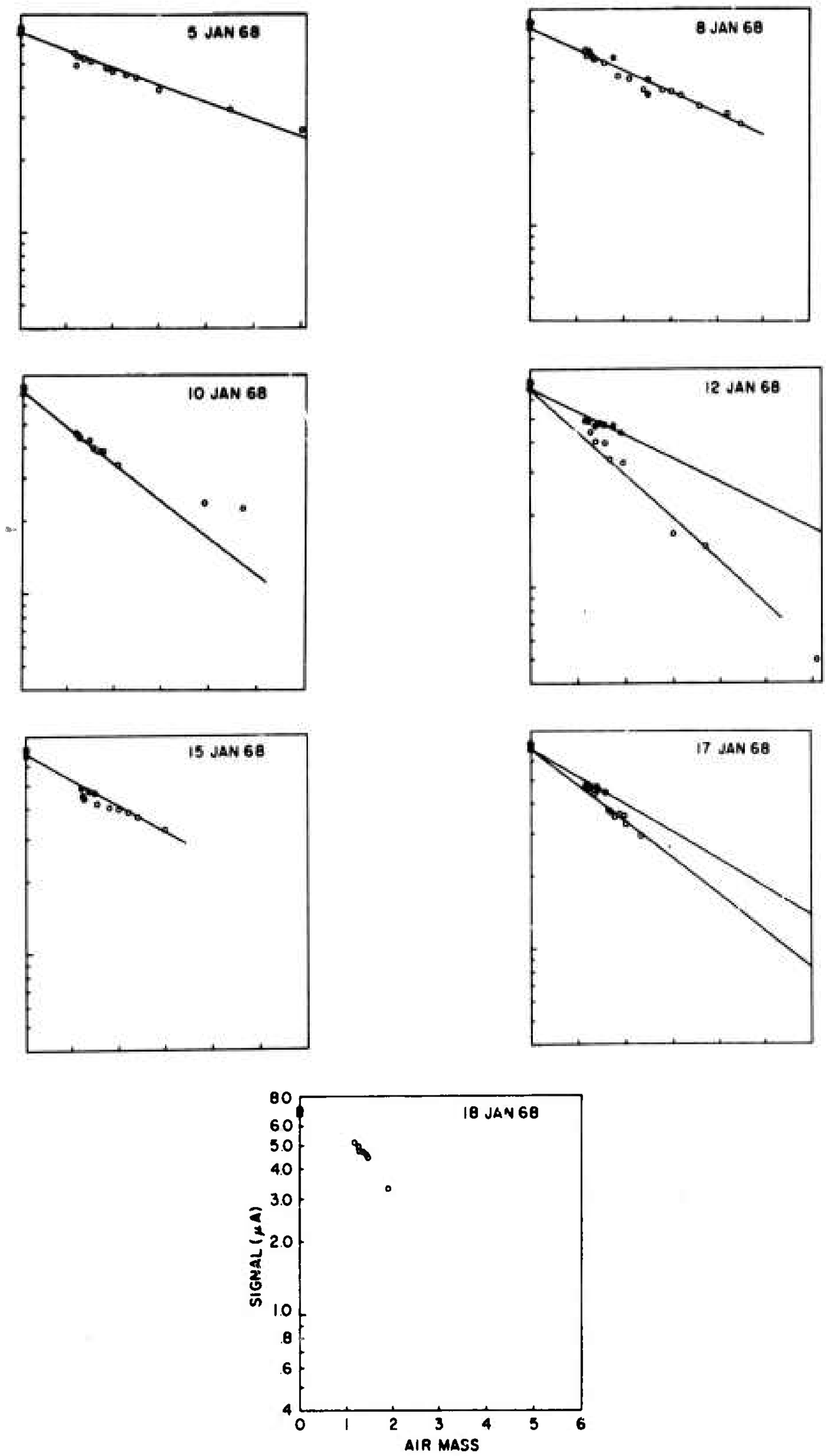
(c) $\lambda = 5000$ Å



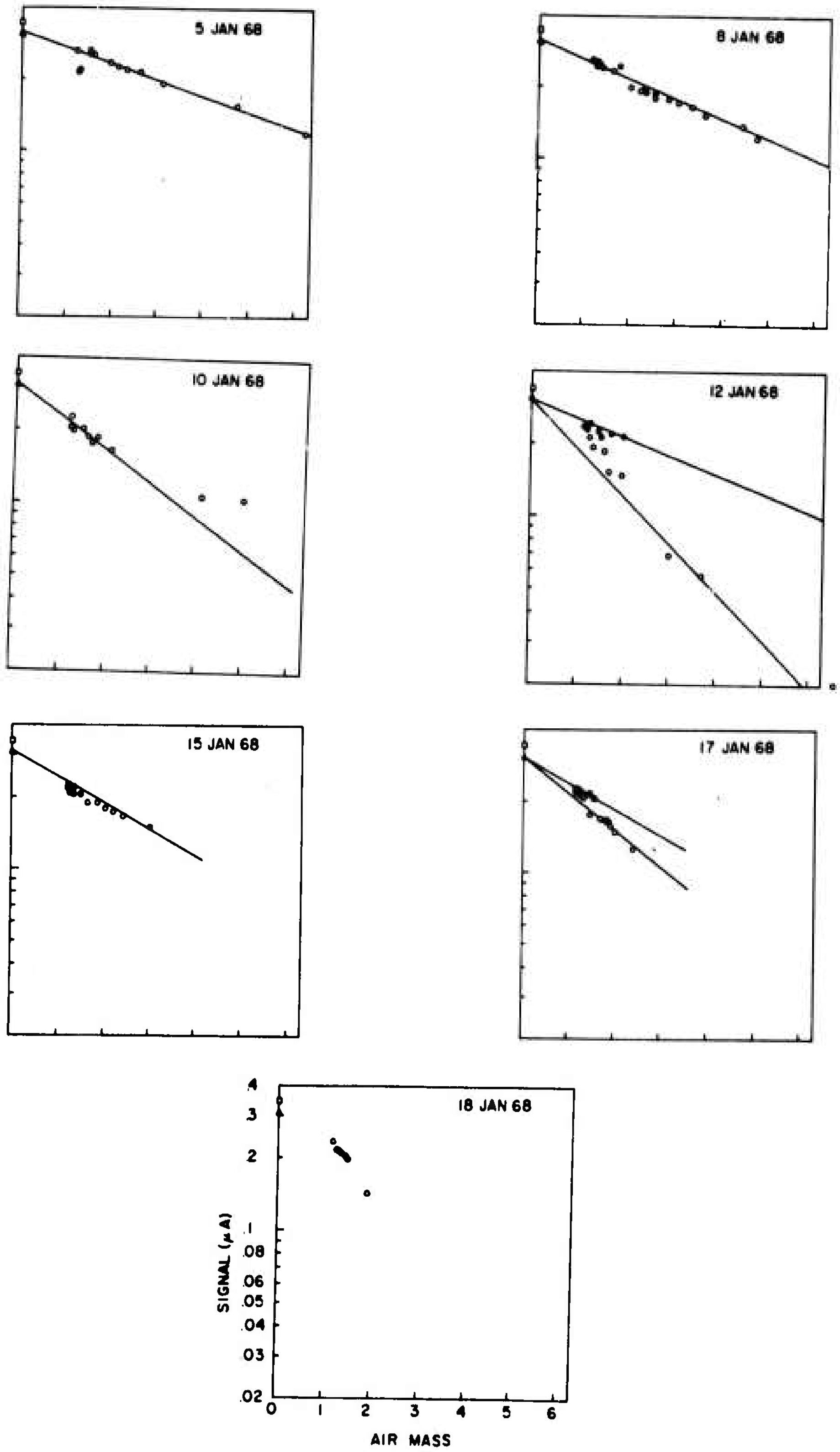
(d) $\lambda = 5500$ Å



(e) $\lambda = 6000$ Å



(f) λ = 6500 Å



(g) $\lambda = 7000\ \mathring{A}$